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Connecting circular economy and energy industry: A techno-economic study for the Åland Islands

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HIGHLIGHTS

- Coupling renewable energy to circular economy in a case region has been analysed.
- Circular economy has potential to manage high variable renewable energy outputs.
- Processing waste materials can increase the value of renewable energy investments.
- Establishing a circular ecosystem requires extensive cooperation between companies.

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ABSTRACT

Energy plays an essential role in circular economy because circular activities such as material processing require power and heat. In parallel, the rate of the transition to renewable energy is not adequate to meet the increasing energy demands. The objective of the study is to evaluate whether circular economy could increase the value of variable renewable energy investments and hence accelerate the transition towards renewable energy. The study involves a combined energy system and material flow analysis. The study is performed on a selected case region as the processes in circular economy and the availability of renewable energies are always local and depend on regional conditions. The Åland Islands was used as a case platform in the study as the electricity generation capacity from wind power in the region is expected to increase significantly in the near future resulting in high variability in the local power supply. Four alternative scenarios are analyzed in which the variable regional renewable energy supply exceeding the local demand is integrated for different purposes: power exports, circular economy, partly electrified transportation sector and district heating. With the highest annual system net profit (0.72 M€), integrating the power production peaks of variable renewable energy into circular economy was found to outweigh the annual economic benefits of power exports (−0.43 M€), the partly electrified transportation sector (−0.50 M€) and district heating (−0.27 M€). Therefore, the value obtained from the products derived from circular processes increased the value of the renewable energy system and would hence promote investments in renewable energy in the region.

1. Introduction

The global targets of the Paris Agreement [1] and national policies concerning climate change mitigation together with significant cost reductions in variable renewable energy (VRE) [2,3] are driving a transition from fossil-based energy systems to ones dominated by renewable energy throughout the world. Although the net capacity addition of renewables has increased every year for nearly two decades [4], the current deployment rate of renewables is not fast enough to meet the set long-term climate goals [5,6]. Directing renewable energy investments to regions where capacity factors and hence energy yields of renewable energy production can be maximized is vital to ensure sufficient progress in the energy transition [7]. However, as the output of variable renewable energy sources does not match the power demand, the regional large-scale deployment of renewables, primarily intermittent wind and solar power, will increase the need for energy system flexibility [8,9]. Flexibility in the energy system is necessary to avoid the curtailment of excess VRE supplies and to increase the adaptability of other power generators during periods of low wind and solar output. Alternative measures to increase energy system flexibility to manage VRE integration have been reviewed. At the core of the alternative measures to increase energy system flexibility to manage VRE

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integration are energy storage, demand side management and different power-to-X strategies, in which excess electricity is converted to thermal energy, gas, hydrogen or used as a charging source in the electrified transportation sector [10,11]. An alternative approach to utilize excess electricity is introduced in [12], where low-cost electricity generated by intermittent energy sources is suggested for producing energy-intensive intermediate products such as pure water, chemicals, alloys and composites to create additional value for renewable energy investments. By processing regional side and waste material streams to become intermediate high-value products, circular economy could provide an additional power demand at times when the regional power supply exceeds local demand. The potential conjunction between circular economy and the resulting low-cost peak power supply from intermittent power sources could thus help accelerate the transition to renewable energy. If a company is able to attain additional value by processing their side and waste material streams into intermediate high-value products during periods of low-cost power supply, the increased material value created by VRE could create incentives for companies themselves to invest more in renewable energy.

Islands provide an interesting subject for VRE integration studies. Most islands are highly dependent on imported energy although islands are often abundant in VRE resources such as wind and solar irradiation [13]. In addition to initiatives to increase energy self-sufficiency, the energy system structures on islands are often simpler in relation to continental regions [14]. With clear system boundaries and their small scale, islands provide a feasible platform to assess and implement new measures to enable the wider adoption of VRE and can therefore also act as blueprints for energy transition in larger continental areas [15]. Flexibility measures to enable higher VRE penetration in island regions have been evaluated in several case studies. Techno-economic analyses for alternative renewable energy system configurations have been conducted for La Gomera (Canary Islands, Spain) [16], where the flexibility potential was recognized in bidirectional vehicle-to-grid charging, in which electric vehicles acted as mobile energy storage devices on the island. The importance of transmission and flexible demand in VRE integration in the Canary Islands archipelago has been highlighted along with coupling energy, transportation and heating sectors with electric vehicles and electric heaters [17]. A pumped hydro storage plant was discovered to be a techno-economical solution to increase wind and solar energy penetration in the Faroe Islands (Denmark) [18]. As for practical examples of renewable energy islands with high VRE penetration, a hybrid system consisting of a wind farm and a pumped hydro storage has been implemented on El Hierro (Canary Islands, Spain) [19], whereas a wind turbine-photovoltaic-electrochemical battery hybrid has been realized in the islands of Tilos (Greece) [20].

The Åland Islands are an autonomous region of Finland located in the Gulf of Bothnia, and have been used as a case platform in several renewable energy system studies on flexibility as the islands aim to become entirely renewable in regards to energy by 2025 [21]. The current energy system of the Åland Islands including both the power and thermal heat sector is described in [22]. To achieve energy autonomy, the Åland Islands intend to increase their installed wind power capacity almost nine-fold from the current 21 MW [23] to approximately 185 MW [24] in the upcoming decade. The significant increase in VRE capacity will result in high fluctuations in the local power supply. Proposed solutions to promote high-level VRE integration in the Åland Islands include, for instance, a highly electrified transportation sector [25] along with heat storage and synthetic fuel production using power-to-gas technologies [14] and flexible combined heat and power generation from domestic biomass [26].

Based on the literature review, circular economy has not been considered as a demand source to utilize the excess power supply from renewable energy on the islands. In this study, excess power supply refers to power that is produced by VRE sources in the case region, but which cannot be utilized locally during the given time frame. The Åland Islands are utilized as a case platform in the study to evaluate the feasibility of integrating excess VRE production into circular economy processes in contrast to three more conventional energy system flexibility alternatives including power exports to neighboring power areas, power-to-electric vehicle charging in a partly electrified transportation sector and power-to-heat conversion via electric heaters for district heat production. The Åland Islands are selected as a case platform for the study due to its substantial upcoming VRE investments and the anticipated resulting variance in the regional power supply [22] and also because the island region is a compact geographical area enabling clear system boundaries for both the energy system and circular economy. The study is performed using a developed mixed integer linear programming-based model, in which the energy system and material flow optimization are combined. The circular ecosystem on the Åland Islands is illustrated by identifying local industries which generate side and waste material streams that could financially benefit from value-adding material circularity.

2. Methodology

The methodology of this study is divided into four main sections. First, a short description of the modelling framework applied in this study is presented. Second, a reference scenario of the energy system of the Åland Islands for the year 2025 is described. Third, three alternative energy system scenarios are constructed for the year 2025 including alternative utilization pathways for the power supply exceeding local demand. Fourth, cost and market assumptions for the scenarios are presented.

2.1. The optimization model

The BRAIN framework, created using Pyomo [27] and CPLEX [28], and initially presented in [22], enables the creation of a hourly-resolved combined capacity planning and dispatch optimization model based on mixed integer linear programming. The model determines the optimal dispatch schedule of power and heat production units, storage systems and power transmission and resolves the optimal capacity of the potential dispatchable unit investments while respecting defined constraints. The objective function of the model aims to maximize the system operating profit, which includes income from sold electricity, district heat and exported electricity, as well as costs from used fuels, OPEX, CO_2 emission allowances, imported electricity and annual investment payments from optimal new investments. In this study, the model was expanded to optimize energy systems in conjunction with selected circular processes. Unit models of circular processes comprising essential process steps were included in the optimization model, and the objective function was set to include operating costs and incomes from the selected circular processes. A more thorough description of the model formulation is presented in Appendix A.

2.2. Establishment of a reference scenario for 2025

The reference scenario in this study represents the energy system of the Åland Islands in 2025 in which the demand for power [29] and district heat [30] have grown according to the consumption growth trends of the past decade. The scenario also includes the planned investments in additional renewable capacity. An hourly time series of the power and district heat demand for the year 2017 was provided by the local transmission system operator Kraftnät Åland and by the local energy company Mariehamns Energi. Both data series were scaled resulting in annual power and district heat demands of 350 GWh_e and 132 GWh_{th} for the year 2025, respectively. Thermal losses of district heat (10.9%) were kept constant with the values from 2017 [31]. The transportation fuel demand for gasoline and diesel for 2025 were also scaled based on the consumption growth trends of the past decade resulting in fuel demands of 111 GWh and 112 GWh for gasoline and diesel, respectively [32].

The wind power capacity in the reference scenario was increased from the current 21–185 MW based on the regional wind power projects in the pipeline [24]. The fleet was divided into two categories of onshore 38 MW (30 MW) and offshore 147 MW (134 MW) turbines based on the location of the existing [23] and planned [24] turbines. The values in the brackets represent new investments in the mentioned turbine type. Wind speed data [33] from the closest observation point for each turbine was converted to the expected hub height by applying wind power law. The wind speeds were converted into wind power output by applying wind power curves from a common supplier of existing onshore [34], existing offshore [35] and new wind turbine investments [36]. The solar PV capacity on the island was only marginal in 2017 [37] and hence the output is not observed on a system level. As for the 2025 scenario, a total solar PV capacity of 15 MW was assumed to exist comprising of residential solar PV installations. The solar PV output was calculated based on solar irradiation data from 2017 [33] and a constant panel efficiency of 14%.

In the 2025 scenario the district heat generation capacity includes the existing 11 MW and additional 5 MW heat production units fueled with solid biomass [30] as well as heavy fuel oil fueled transportable production capacity, serving as a back-up reserve [31] totaling 45 MW [30]. The current district heat generation capacity in the Åland Islands also includes two CHP units fueled by heavy fuel oil [30]; however, these units are expected by be decommissioned by 2025 and were therefore not included in the simulations. A constant thermal unit efficiency of 90% was assumed for both biomass boilers whereas the efficiencies of the oil boilers applied as a back-up reserve are expected to be 86%.

The hourly electricity price data in the Nord Pool SE3 market area in 2017 [38] was applied to represent the market conditions in 2025 in Åland Islands. The power transmission was aggregated into a single 180 MW interconnector [39] to reduce the model complexity. In reality, the Åland Islands is connected to the market areas of Finland and Sweden with separate power transmission lines [40].

2.3. Establishment of the studied scenarios

Three alternative scenarios along with the reference scenario are analyzed in this study to evaluate the potential of circular economy to increase the value of a renewable energy system. The studied scenarios were: (1) the power-to-circular economy (P2CE) scenario; (2) the power-to-electric vehicles (P2EV) scenario; and (3) the power-to-heat (P2H) scenario. The three alternative scenarios were built on top of the reference scenario, and hence all parameters related to the energy system itself remained the same as in the reference scenario unless otherwise stated. In the four scenarios (including the reference scenario), the VRE supply exceeding local demand may be used for different purposes. In the reference (Base) scenario, power peaks are exclusively exported to the neighboring power areas of Sweden and Finland. The excess power supply may also be exported in the three alternative scenarios. However, in the P2CE scenario, the excess power supply may also be applied in the circular processes defined later. In the P2EV scenario, the excess supply can be used for charging electric vehicles whereas in the P2H scenario, the excess power supply can be converted into district heat via electric boiler. The detailed construction of each alternative scenario is presented in the following paragraphs.

To define the circular processes for excess power supply utilization in P2CE scenario, the material flow characteristics of the Åland Islands had to be evaluated to detect potential waste streams applicable for value-adding material processing. The evaluation was conducted by reviewing official statistics, the research literature and publicly available data from companies located in the Åland Islands and hence the illustrated circular ecosystem could have potential for practical implementation. Several circular processes already exist in the Åland Islands. Side products such as branches, tops, bark and sawdust from the local forest industry are already exploited in domestic district heat production [41] and as of 2017, residues from local wood processing operations represented approximately 85% of the fuel used for district heat production in the main district heating network of the Åland Islands [30]. Smaller heating networks in the region are also fueled by residues from the local forest industry [41] and partly by biogas from a local milk processing plant [42]. The local chip factory [43], milk processing plant [42] and wastewater treatment plant [44] all own individual biogas production units, in which biodegradable side products are converted into energy applied mainly in the internal processes of the companies themselves. A land-based fish farm plans to build a biogas production unit to convert wastewater sludge from fish cultivation water and residues from fish slaughtering processes to biogas for internal energy use [45]. The recirculating aquaculture system used in the fish farm, in which cultivation water is continuously purified and reused, could also provide a potential demand source for oxygen to optimize fish growth. Furthermore, a mobile wastewater treatment unit is being piloted in the Åland Islands to extract suspended solids, phosphorous, nitrogen and carbon from wastewater of a fish processing plant [46]. In addition, fish residues from local fish farming have been applied in small-scale biodiesel production largely utilized by a local bus company [47].

In 2016, the total amount of generated waste in Åland Islands was approximately 45,600 tons, consisting of 42,600 and 3000 tons of non-hazardous and hazardous waste, respectively [48]. The content of the non-hazardous waste is depicted in Fig. 1. The majority of the waste treated in the Åland Islands was biodegradable waste, which was largely composted. Household and similar waste was transported to Finland and Sweden for thermal waste incineration. Recyclable waste including paper, metal, glass, plastic, and rubber was mainly transported to be treated outside the islands. In addition, all hazardous waste was exported. As the waste volumes of the exported recyclable material flows are relatively small, they are not considered as potential waste streams for upgrading processes in this study. Furthermore, the available data related to composition of the recyclable waste streams, such as plastics, was considered insufficient for an in-depth analysis of the potential utilization pathways. Therefore, in this study, the biodegradable waste streams are at the core of the circular ecosystem illustrated for the Åland Islands.

Fish residues, are an untapped resource in Åland Islands as they are currently mainly treated with formic acid and sold as fur animal feed to northern Finland [50]. The annual amount of fish residues produced in the Åland Islands can reach up to 3000 tons including fish residues from local fish farming and from local fish processing operations where both locally farmed and imported fish are processed [47]. The majority (99%) of fish farmed in the Åland Islands are rainbow trout and their residues consist of fat (60%), protein (20%) and nutritious water (20%) [47]. According to the composition of the fish waste stream, this study assumes the annual yield of waste oil and waste protein fractions from fish residue to equal 1800 and 600 tons, respectively. In this study, the separated oil fraction was applied in biodiesel production, whereas the extracted protein fraction was used as a substrate for biogas production. The upgrading process of fish waste begins with a fractionation step, in which formic acid, electricity and heat are applied to separate waste oil and other fish remains including nutritious water and protein fractions from the residue [51]. The waste oil is further processed into biodiesel with methanol, an alkaline catalyst, electricity and heat resulting in output streams of biodiesel and crude glycerin [51]. The upgrading process takes place in a single unit, in which fish residue from individual farmers and operators on the island are collected. In other scenarios than P2CE, including the reference scenario, the residue was sold as animal fur feed with an associated price of 150 €/t [47], instead of processing it into biodiesel.

An investment in a centralized biogas plant has been discussed in the Åland Islands [52] and hence all scenarios, including the reference scenario, assume that an investment in a biogas unit converting available biodegradable waste in the Åland Island into biogas has already been made. The biogas potential has been studied in the Åland Islands [53] and the methane yield of the referred study (2.06 million m^3) is

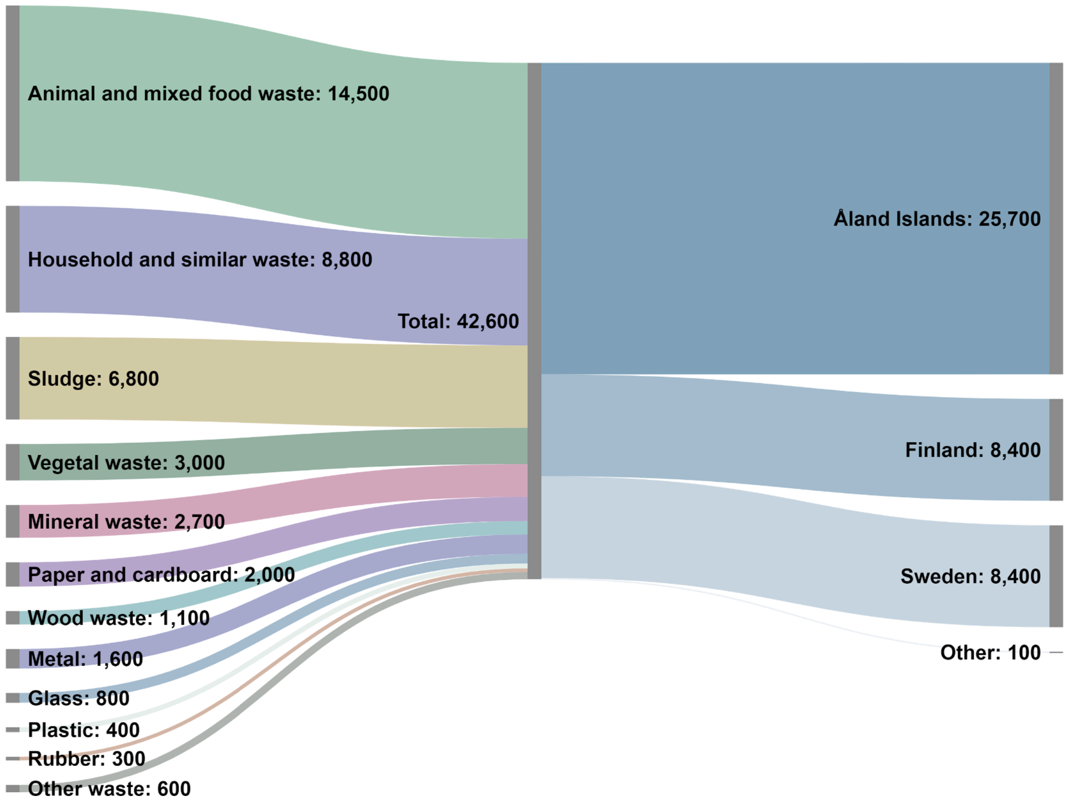

Fig. 1. Breakdown of non-hazardous waste material streams in the Åland Islands in 2016. Data derived from [49].

applied to evaluate biogas supply in the scenarios excluding the P2CE scenario. For the purpose of establishing circular processes in the P2CE scenario, some modifications were made to the biodegradable waste supply of the given study based on findings from the literature. The annual amount of fish waste in the biodegradable waste feed-in was increased from 560 t/a to 600 t/a in accordance with [47], increasing the annual methane yield of fish waste by 15,000 m^3 by applying dry substance and methane yield estimates from [53]. Moreover, five mobile wastewater treatment units are expected to be piloted in the Åland Islands to partially purify wastewater from fish slaughtering and processing operations. The dry matter fraction from the wastewater treatment units is expected to increase the annual methane yield by 56,300 m^3. An additional biodegradable waste stream was also assumed to be derived from a local brewery, which tripled its annual production capacity in 2017 to 2.5 million liters of beer [54]. Currently, the mash from the brewery is fed as animal feed to local cattle and pigs. In this study, the mash is instead utilized as a biodegradable waste fraction for biogas production. The estimated annual mash yield of 438 tons with a water content of 75% [55] is expected to result in an additional methane yield of 43,800 m^3. With given modifications, the annual methane (CH_4) yield was increased from 2.06 million m^3 [53] to 2.18 million m^3. As the methane concentration in the raw biogas is expected to remain constant (63%) to the referred study [53] the hourly raw biogas supply of the biogas plant is estimated to be 395 m^3 throughout the year.

Besides some impurities, the remaining fraction of biogas (37%) consists of carbon dioxide (CO_2) [56]. The CO_2 fraction obtained from the generated biogas could be upgraded to biomethane in a methanation process with hydrogen derived from an electrolyzer. Hydrogen production by water electrolysis and the subsequent conversion of hydrogen and carbon dioxide to methane is considered a promising option to utilize low-cost power supply during peak production periods of fluctuating VRE generation [57,58]. As the electricity price is considered an important factor in the economic feasibility of electrolysis and methanation processes [59,60], the low-cost power supply during peak production periods of VRE in the Åland Islands is expected to increase the profitability of these processes. Therefore, an alkaline electrolyzer (2.6 MW_e) with 67% efficiency [60] was combined with the biogas plant. The capacity of the electrolyzer was determined based on the maximum amount of electricity required to produce hydrogen capable to stoichiometrically convert all the available carbon dioxide (0.288 t/h) from raw biogas into biomethane in a Sabatier reaction [57,58]. Before the methanation process, carbon dioxide and methane from the raw biogas feed are separated, resulting in purified fractions in both streams. The purified fraction of carbon dioxide, upgraded to biomethane with hydrogen, is later referred to as synthetic natural gas (SNG). The combined feed of the purified methane and the generated SNG is later referred to as biomethane which is applicable for use as a transportation fuel in parallel to methane. The generated oxygen in the electrolysis could be partially applied in the land-based fish farm located in the Åland Islands and the derived process heat from the electrolyzer could be applied as district heat. An intermediate, short-term compressed hydrogen storage was added to the system to partly decouple the hydrogen production from the biological methanation process.

Eventually, the circular processes selected to utilize excess power supply in Åland Islands were fish waste fractionation and biodiesel production along with raw biogas upgrading through a biological methanation process. Therefore, simplified unit models of fish waste fractionation, biodiesel production, electrolysis and biological methanation were included in the optimization model as additional power demand nodes. With respect to the circular processes, the model is able to optimize alternative options on an hourly basis. In the P2CE scenario, the model optimizes whether biogas is upgraded to biomethane or sold as a raw biogas, and if fish waste is fractionated and converted to biodiesel or sold as animal fur feed instead of the conversion to a higher-value product. A visual representation of the studied circular processes in the P2CE scenario is shown in Fig. 2 along with the most essential process parameters. Available fish waste volumes and the subsequent fractions of oil and protein are derived from [47] whereas the

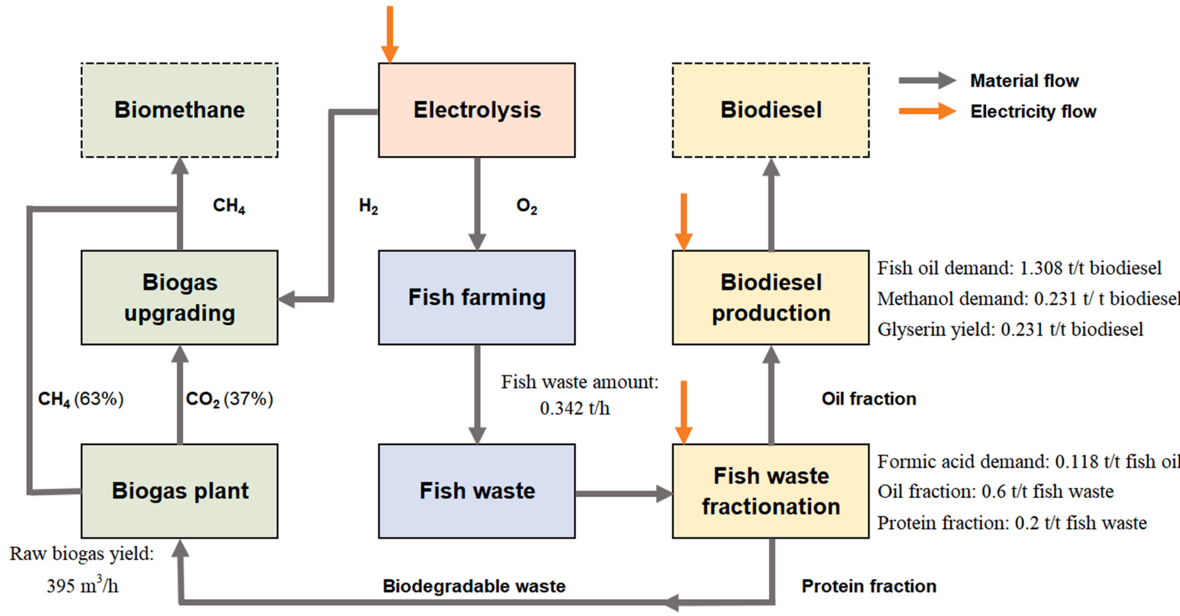

Fig. 2. Simplified material flow chart for the illustrated circular ecosystem for the Åland Islands. Output streams of the circular ecosystem are outlined with a dashed line. The orange line represents the additional power demand nodes added to the system. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

parameters related to fish waste fractionation and biodiesel production are derived from [51]. The output streams of the circular ecosystem are outlined with a dashed line.

Whereas the P2CE scenario is based on actual material flow volumes in the Åland Islands, the following P2EV and P2H scenarios are based on simpler assumptions with the aim of providing a basis to compare the feasibility of circular economy in managing high VRE outputs. In the P2EV scenario, electric vehicles are considered as an additional power demand node in the system. Assuming that 25% of the car stock of the Åland Islands in 2017 [61] would be replaced by electric cars, 5960 electric vehicles will be in use by 2025. The electric vehicles were assumed to consume 0.2 kWh per kilometer [62]. With daily road transportation demand for each car at 41 km [63], the estimated daily power demand for one electric vehicle equals 8.2 kWh. In the model, charging was set to be allowed in a six-hour period between the hours of 23 and 05 with a maximum hourly charging rate of 3.8 kW [64]. Charging was set to be possible from the grid to the vehicle without a possibility for bidirectional vehicle-to-grid charging. In the P2H scenario, an electric boiler was added to the modelled system to provide an additional demand source for the excess VRE supply and an alternate option for heat generation in the district heating network. For the boiler, a capacity of 10 MW and thermal efficiency of 95% was selected. The scenario-wise main supply and demand parameters are shown in Table 1.

Table 1
Main supply and demand technologies applied in the scenarios. Values in brackets represent new wind power investments.

Technology	Unit	Scenario			
		Base	P2CE	P2EV	P2H
Wind onshore	MW_e	38 (30)	38 (30)	38 (30)	38 (30)
Wind offshore	MW_e	147 (134)	147 (134)	147 (134)	147 (134)
Solar PV	MW_e	15	15	15	15
Biomass boiler #1	MW_{th}	11	11	11	11
Biomass boiler #2	MW_{th}	5	5	5	5
Oil boiler	MW_{th}	45	45	45	45
Transmission capacity	MW_e	180	180	180	180
Fish waste fractionation	kW_e/ kW_{th}		8.4/ 48.2		
Biodiesel production	kW_e/ kW_{th}		9.4/7.2		
Electrolysis	MW_e		2.6		
Methane yield	million m^3	2.06	2.18	2.06	2.06
Electric vehicles	MW_e			23	
Electric boiler	MW_e				10

2.4. Cost and market assumptions applied in the scenarios

Investment costs for new power production technologies applied in all scenarios are presented in Table 2. The table also includes investment costs related to the circular processes covered in this study. For all the investments, a weighted cost of capital of 7% is applied to determine the annual investment payment. The electrolyzer applied in the P2CE scenario is equipped with a hydrogen compressor with an investment cost of 230 €/kW_e [65] of electrolysis input power. The hydrogen tank with an investment cost of 13.5 €/kWh_{H2} [65] is scaled to store one hour production of hydrogen at full load.

The main market parameters applied in the scenarios are presented in Table 3. The price of biomethane was set at an optimistic value of 80 €/MWh [60]. As the methane content in raw biogas is lower in comparison to biomethane, the price of biogas was assumed to be lower (60 €/MWh). As the energy content of biodiesel (11.5 MWh/t [51]) equals the energy content of diesel (11.5 MWh/t) the income from biodiesel was expected to be equivalent to consumer diesel prices excluding value-added tax (2017: 0.98 €/l [68]).

3. Results and discussion

In this section, the cost-optimal operation and the value of the studied scenarios are evaluated. Annual power and district heating structures for the four scenarios are analyzed in addition to the annual cost breakdown of the studied scenarios. A detailed cost analysis is conducted for the value-adding products in the circular ecosystem of the P2CE scenario. Furthermore, a sensitivity analysis is carried out to evaluate the impact of alternate product prices (biogas versus biomethane and fish waste versus biodiesel) on the profitability of the

Table 2
Investment parameters applied in the scenarios for power generation and circular economy technologies.

Process	CAPEX		Fixed OPEX [% of CAPEX]	Lifetime (a)	Source
Onshore wind	975	€/kW	2.3	30	[65]
Offshore wind	1300	€/kW	2.3	30	Assumption based on [14]
Solar PV	715	€/kW	1.4	30	[65]
Electrolysis	12,301	€/kW	2.5	20	[60,65]
Biological methanation	730	€/kW_{SNG}	2.5	20	[60]
Fish waste fractionation	420	€/$t_{fish\ waste}$	2.5	15	Assumption based on [47]
Biodiesel production	300	€/$t_{biodiesel}$	2.5	15	Assumption based on [66]
Hydrogen storage	13.5	€/kWh	0.14	30	[65]
Electric boiler	65	€/kW	1.6	20	[67]

[1]Includes compressors for hydrogen storage.

Table 3
Main market parameters applied in the scenarios.

Parameter	Cost		Source
Electricity (average) price	31.2	€/MWh	[38]
District heat price	80	€/MWh	[69]
Biomass price	22	€/MWh	[70]
Oil price	45	€/MWh	[14]
CO_2 emission allowance price	30	€/t	[71]
Biogas price	60	€/MWh	Assumption based on [60]
Biomethane price	80	€/MWh	[60]
Biodiesel price	107	€/MWh	[68]
Fish waste price	150	€/t	[47]
Formic acid price	600	€/t	[60]
Methanol price	390	€/t	[60]
Glycerin price	200	€/t	[51]

circular ecosystem in which biomethane and biodiesel are produced from the applied waste streams.

The system optimization results show variation between the studied scenarios in annual power consumption, import and export volumes, as well as in annual district heat generation quantities with the associated fuels as seen in Table 4. In accordance with the simulation results, the local power generation in the Åland Islands is dominated by variable wind power (611 GWh/a) whereas the role of solar PV (14 GWh/a) is only supplementary. Consequently, the amount of generated electricity was almost twice the power consumption (350–370 GWh) of the Åland Islands in all scenarios. In comparison to the Base scenario, the annual power consumption increased in the P2CE, P2EV and P2H scenarios as additional power demand nodes were added to the analyzed systems. The integration of the local power supply to the Åland Islands increased in the P2CE, P2EV and P2H scenarios as the amount of power exported decreased in comparison to the Base scenario. The amount of imported electricity increased in the P2EV scenario and slightly in the P2CE scenario. In the former scenario, the availability of wind and solar power was not sufficient at all times to meet the power demands of electric vehicles within the given daily charging period. Similarly, in the latter scenario, the biodiesel production from fish waste was optimally operated continuously, increasing the demand for imported electricity at times when the local supply was not adequate to meet both the local power demand and the power demand of the additional circular process.

Table 4
Power and district heat generation structures of the simulated scenarios. Change (%) describes the relative change of the value compared to the Base scenario.

Parameter	Base	P2CE	P2EV	P2H
Power consumption (GWh)	350	364	370	364
Change (%)		3.9%	5.0%	4.1%
Power export (GWh)	346.5	333.0	329.7	332.1
Change (%)		−3.9%	−4.9%	−4.2%
Power import (GWh)	71.6	71.6	74.3	71.6
Change (%)		0.1%	3.8%	0%
District heat generation by boilers[1] (GWh)	132	128	132	132
Change (%)		−3.0%	0%	0%
Biomass consumption (GWh)	107.7	105.8	107.7	107.7
Change (%)		−1.8%	0%	0%
Oil consumption (GWh)	24.3	22.3	24.3	10.7
Change (%)		−8.2%	0.0%	−56.0%

[1] Includes also an electric boiler in the P2H scenario.

As seen in Table 4, the added circular processes in the P2CE scenario increased the local power consumption in the Åland Islands by 3.9% in comparison to the Base scenario. The increase in power consumption depended on the energy intensity of the selected circular processes. Consequently, in the P2H and P2EV scenarios, more local production was integrated in the energy system, as the share of power exports was lower than in the P2CE scenario. Therefore, the power demand of electric vehicles or heat conversion from the excess VRE supply would provide a better option to increase the integration of the local power supply in comparison to the circular ecosystem with the defined system constraints.

The fuel consumption for district heat production reduced in the P2CE and P2H scenarios compared to the Base scenario. In the P2CE scenario, the electrolyzer contributed to district heat production by supplying process heat to the district heating network, whereas in the P2H scenario, the electric boiler converted the excess power supply to district heat. In the P2H scenario, the oil consumption decreased significantly (13.6 GWh and 56%) while the biomass consumption remained constant being the less expensive district heat production method. The reduction in oil consumption was high in the P2H scenario, as the electric boiler was able to produce heat independently of other processes, allowing the reductions to focus on the peak production of district heat with oil. In the P2CE scenario, the process heat derived from the electrolyzer reduced both oil consumption (1.9 GWh or 2%) and biomass consumption (2.0 GWh or 1.8%). The achieved reductions were smaller than in the P2H scenario as the process heat availability of the electrolyzer was dependent on the downstream processes: if biogas is not upgraded, hydrogen production is not required. It should be also noted that the maximum hourly potential of heat derived from alternative sources rather than biomass and oil were notably smaller in the P2CE (0.9 MW) scenario in relation to the P2H (9.5 MW) scenario, which led to a difference between the scenarios.

The annual income and cost breakdown of the scenarios is presented in Fig. 3, with the structure being the same in all the scenarios. The annual income was formed from locally sold and exported electricity, sold district heat, and sold fuels. Annualized investment costs were the largest contributor to the annual system costs. In addition, costs were induced by fixed and variable operating costs as well as imported electricity. The additional investments related to the additional power demand nodes in the assessed scenarios did not lead to prominent variations in the annual net profits. However, only the P2CE scenario achieved a positive annual net profit (0.72 M€) with the applied cost assumptions and is hence the most feasible option economically. As the Base (−0.43 M€), P2EV (−0.50 M€) and P2H (−0.27 M€) scenarios led to negative annual net profits, the value increase derived from processing the selected side and waste material flows outweigh the economic benefits of power exports as well as the income derived from the sold

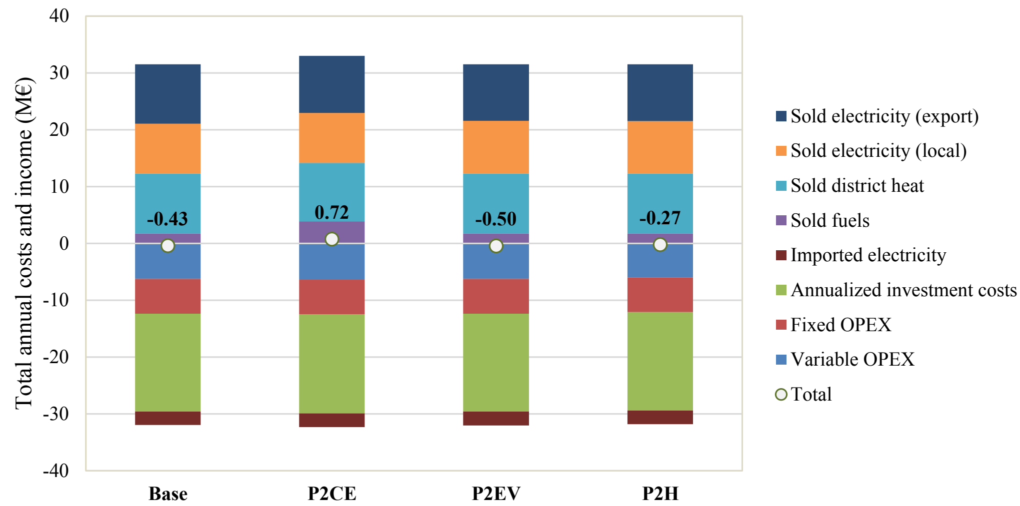

Fig. 3. System annual income and cost structure of the simulated scenarios. The dots indicate the annual net profit of the scenarios.

electricity to electric vehicles or the sold district heat from power-to-heat conversion in the electric boiler.

In comparison to the other scenarios, the P2CE scenario derived more income from the sold fuels which were produced by the selected side and waste material streams as seen in Fig. 4. In the Base, P2EV and P2H scenarios, the annual raw biogas yield was 20.8 GWh, resulting in an income of 1.25 M€ when applying the biogas price of 60 €/MWh. In addition, in these scenarios an income of 0.45 M€ was derived from fish waste (3000 t) which was sold as animal fur feed with the associated price of 150 €/t. In the P2CE scenario, the annual raw biogas yield was 0.8 GWh higher (21.6 GWh) due to the additional biodegradable waste sources added to the system, from which 8.8 GWh were sold as raw biogas (60€/MWh) for an income of 0.53 M€. The remaining share of raw biogas (12.8 GWh) was directed to the biogas upgrading unit where an additional SNG yield of 7.5 GWh was achieved by converting carbon dioxide from the raw biogas to biomethane. The pure biomethane (80 €/MWh) of 20.3 GWh resulted in a total income of 1.62 M€. The biogas upgrading process and hence the production of biomethane from the carbon dioxide was however limited by the availability of hydrogen from the electrolyzer, which consumed only 13.4 GWh of electricity and hence did not reach its annual electricity consumption potential (22.8 GWh). Consequently, the hydrogen output was not sufficient to convert all the carbon dioxide from raw biogas into biomethane.

In addition to biomethane, an additional income in the P2CE scenario (1.7 M€) was derived from fish waste which was converted into biodiesel (15.7 GWh; 107€/MWh). As both fish waste fractionation and biodiesel production reached their combined maximum potential for electricity consumption (0.15 GWh/a), the maximum amount of biodiesel (15.7 GWh) was produced. The biodiesel and biomethane could be used to replace transport fuels on the islands. When compared to the assumed gasoline and diesel demand of 2025 totaling in 223 GWh, the fuels in the P2CE scenario could theoretically replace 16.1% of the total consumption, with 7.0% from biodiesel and 9.1% from biomethane. In addition, the raw biogas could be used to produce 7.9 GWh of district heat, assuming a conversion efficiency of 90%, which would contribute 6.0% of the annual district heat demand. In both the P2EV and P2H scenarios raw biogas could replace 18.7 GWh and 14.2% of district heat demand with same conversion efficiency (90%), however transportation fuels would not be generated.

As fuel production created the largest benefits in the P2CE scenario in relation to the alternative scenarios, the sensitivity of product prices (biogas, biomethane, fish waste, biodiesel) on the annual yields of both biomethane and biodiesel are further studied. For both fuels, the model was able to optimize between two options on an hourly basis: whether biogas was upgraded to biomethane or sold as a raw biogas, and whether fish waste was fractionated and converted to biodiesel or sold as animal fur feed instead of the conversion. First, the impact of both raw biogas and biomethane prices on the annual biomethane yield was studied. Second, the effect of the fish waste and biodiesel price on the annual biodiesel yield was evaluated.

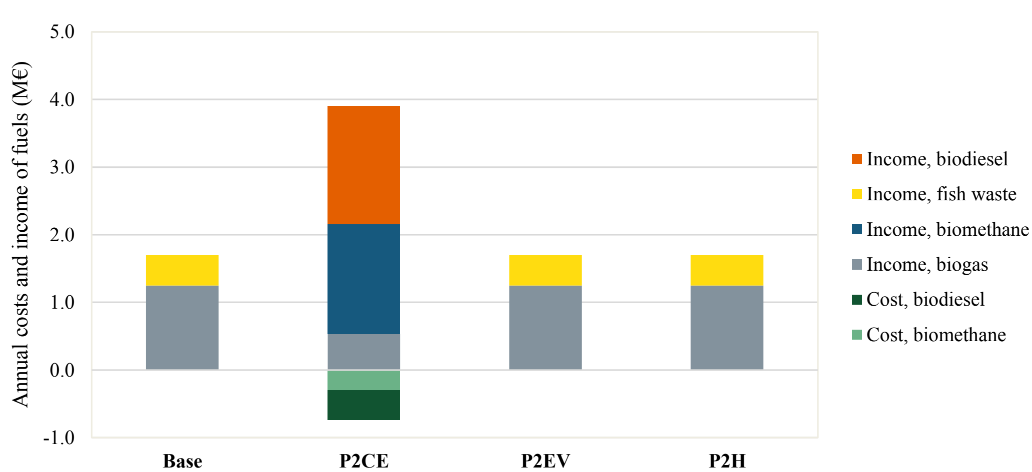

Fig. 4. Annual income and cost structure of fuel production in the simulated scenarios.

The prices of the assessed products were varied in steps of 10% to determine the break-even prices between the options in Fig. 5. As seen from the figure, when decreasing the price of biogas (a), biogas upgrading becomes a more favorable option but the yield of biomethane from the biogas upgrading unit only marginally increases. On the other hand, if the price of biogas is increased by 40%, the value of biogas (84 €/MWh) exceeds the value of biomethane (80 €/MWh). However, the yield of biomethane is only halved. As biogas upgrading creates income also from sold district heat due to hydrogen production, the option is still more feasible than the combination of selling raw biogas and exporting the electricity during power production peaks. When decreasing the value of biomethane (b) by 10% in the model, the yield of biomethane begins to decrease linearly until almost no biomethane is produced at −30% of the biomethane value (56 €/MWh) which is below the value of raw biogas. When the value of biomethane is increased, the yield of biomethane increases only marginally, showing a similar behavior as when reducing the price of biogas in (a). As local power generation is not available at times, the annual biomethane yield cannot possibly reach its theoretical potential (34.3 GWh). The potential is also limited due to modelling assumptions: the available raw biogas had to be fully upgraded or not upgraded at all on an hourly level. Therefore, raw biogas could not be partially upgraded during hours with only a small amount of electricity available for hydrogen production. The price variations in fish waste (c) and biodiesel (d) did not have impact on the annual biodiesel yield. With the given cost assumptions, biodiesel production was found to be always more profitable because the value of fish waste is almost tripled during the upgrading process. For example, the profit for one ton of fish waste as animal fur feed was 150 € whereas the profit for biodiesel processed from it was roughly 410 €. The value increase is mainly explained by the high expected fat content of the fish, which directly correlates with the biodiesel yield.

4. Conclusion

This study evaluated whether circular economy could increase the value of a renewable energy system in comparison to more conventional alternatives for intermittent power supply utilization by applying a combined energy system and material flow optimization. The Åland Islands were used as a case platform as significant expansions in the local variable renewable energy capacity in the near future will result in high deviations in the local power supply. Instead of continuing to export the production exceeding the local demand, part of the electricity could be utilized to power electric vehicles to generate district heat or to power local circular economy processes which aim to upgrade side and waste material streams into higher-value products. If upgrading the side and waste materials into higher-value products with the intermittent variable renewable energy supply would bring financial benefits to a company through increased material value, the company itself would have incentives to invest in renewable energy. This is because the circular material upgrading processes would increase the value of the renewable energy investments. As a result, circular economy would act as a catalyst for energy transition. In order to evaluate the hypothesis, a model of the

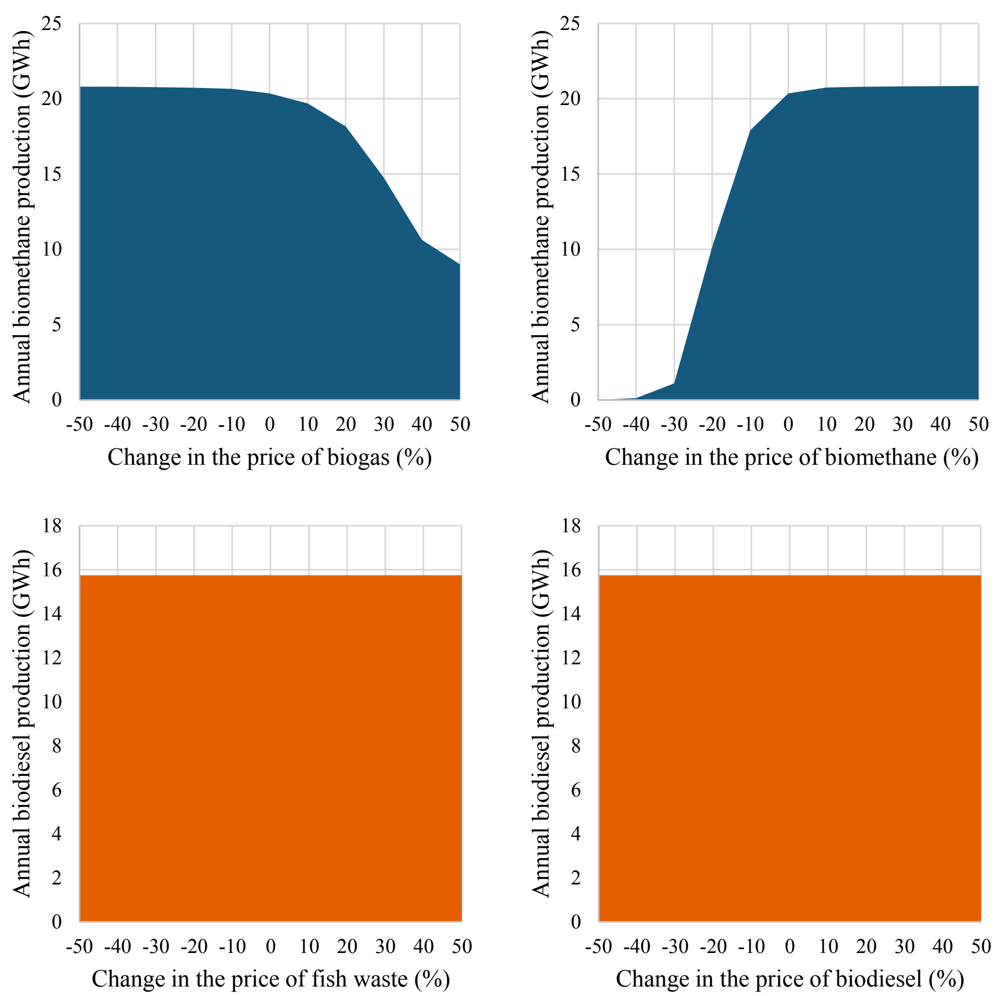

Fig. 5. Sensitivity analysis for the annual production of biomethane as a function of (a) price of biogas and (b) price of biomethane, and for the annual production of biodiesel as a function of (c) price of fish waste and (d) price of biodiesel in the power-to-circular economy scenario.

circular ecosystem was created for the Åland Islands on the basis of gathered material flow information based on official statistics, research literature and publicly available data from companies located in the Åland Islands.

The analysis of the study shows that increased material value via the utilization of local power production peaks in regional circular processes can increase the economic profitability of the energy system. According to the results, the energy system combined with circular processes (0.72 M€) was more economically feasible than the alternative of exporting the production exceeding the local demand (−0.43 M€), partly electrifying the transportation sector (−0.5 M€) and generating district heat (−0.27 M€) in terms of system's annual net profit. However, the potential to increase the value of the system was constrained by two factors: the amount of electricity that can be integrated, and the maximum capacity of the circular processes. In this case, the benefits were limited by the local availability of biodegradable feedstock for biogas and biodiesel production, as well as the variable renewable energy for hydrogen production required for the upgrading of biogas. Furthermore, when creating a circular ecosystem, closed-loop material cycles were found to already exist in the Åland Islands. For example, several companies already converted their own biodegradable side products into biogas and further into energy, and the side products from the wood industry were already being used for local district heating. Therefore, a circular ecosystem could not be created by directly connecting the material and energy streams of different processes but would require the integration of technologies which are novel to the system.

Synergies of connecting energy system with circular economy should be studied on a regional level as circular processes are always local. Although the study shows circular economy to be an economically attractive option, both the effect of the assumptions and the practical requirements should be considered. The study assumed a value increase and therefore a higher price for the upgraded circular economy products (upgraded biogas and biodiesel) compared to the unprocessed alternatives (raw biogas and fish waste). The product values were considered realistic for the studied system, as they were estimates based on national values. However, some uncertainty is present related to the investment costs for the circular economy processes as well as the material flow volumes. While investment costs were available for similar systems, for example fractionation or biodiesel production, the values were scaled based on the production capacities of the studied system. As the data for the material flow volumes was aggregated from multiple sources, the assumed volumes do not necessarily reflect the real situation. Furthermore, most of the material flows were assumed to be continuous and equally distributed. If the material flows were available in batches with varied volumes, less variable renewable energy could potentially be used in the circular economy processes. On practical level, the created circular ecosystem would require changes to the current system, and therefore cooperation between local companies. As for the Åland Islands, the fish waste sources are currently separated in different locations and would require transporting to a centralized processing location. Similarly, all the biodegradable waste streams generated in the system should be collected to be processed by one centralized biogas unit. If such a unit were not implemented, the income from upgrading the biogas would decrease, and consequently so would the feasibility of the circular economy scenario. The other alternative scenarios involved fewer limitations regarding the required investments: in reality, the system could be enabled by private consumers investing in electric vehicles or a district heating company. Therefore, the study highlights how circular economy is able to create economic benefits but also faces non-economic barriers before the benefits can be realized from a conceptual level to reality.

Table A1
Symbols used in the model equations.

Notation	Description
p	Parameter
v	Variable
t	Hour index
T	Set of hours (1 … 8760)
u	Unit
U	Set of units

CRediT authorship contribution statement

Kirsikka Kiviranta: Methodology, Investigation, Writing - original draft, Visualization. **Tomi Thomasson:** Methodology, Software, Validation, Writing - review & editing. **Jonne Hirvonen:** Conceptualization, Investigation. **Matti Tähtinen:** Conceptualization, Funding acquisition, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Model description

The optimization model operates at an hourly resolution with full foresight throughout the year. The symbols used in the model equations are introduced in Table A.1.

Objective function

The objective function (Eq. (A.1)) of the model includes the cost and income terms relevant for the studied system, which consist of the income from sold electricity (Eq. (A.2)), the income from sold district heat (Eq. (A.3)), the income from exported electricity (Eq. (A.4)), fuel costs (Eq. (A.5)), other variable operating costs (Eq. (A.6)), emission allowance costs depending on the fossil fuel share in the unit's fuel mix (Eq. (A.7)), and costs from imported electricity. In addition, the objective function includes income terms for sold biogas and biodiesel as well as cost terms for biodiesel production, which are introduced later.

$$v^{\mathrm{obj}} = \sum_{t\in T}\begin{pmatrix} v_t^{\mathrm{in,el}} + v_t^{\mathrm{in,th}} + v_t^{\mathrm{in,export}} + v_t^{\mathrm{in,biogas}} + v_t^{\mathrm{in,biodiesel}} \\ -v_t^{\mathrm{cost,fuel}} - v_t^{\mathrm{cost,OM,var}} - v_t^{\mathrm{cost,emission}} - v_t^{\mathrm{cost,import}} - v_t^{\mathrm{cost,biodiesel}} \end{pmatrix} \tag{A.1}$$

$$v_t^{\mathrm{in,el}} = (p_t^{\mathrm{solar}} + v_t^{\mathrm{wind,local}})\cdot p_t^{\mathrm{price,el}} + v_t^{\mathrm{el,vehicles}}\cdot p_t^{\mathrm{price,el}} \tag{A.2}$$

$$v_t^{\mathrm{in,th}} = \sum_u v_{u,t}^{\mathrm{th}} \cdot p^{\mathrm{price,th}} + (v_t^{\mathrm{th,heat}} + v_t^{\mathrm{th,circular}}) \cdot p^{\mathrm{price,th}} \quad (A.3)$$

$$v_t^{\mathrm{in,export}} = v_t^{\mathrm{wind,export}} \cdot p_t^{\mathrm{price,el}} \quad (A.4)$$

$$v_t^{\mathrm{cost,fuel}} = \sum_u p_u^{\mathrm{fuel,nom}} \cdot v_{u,t}^{\mathrm{load}} \cdot p_u^{\mathrm{price,fuel}} \quad (A.5)$$

$$v_t^{\mathrm{cost,OM,var}} = \sum_u p_u^{\mathrm{fuel,nom}} \cdot v_{u,t}^{\mathrm{load}} \cdot p_u^{\mathrm{cost,OM,var}} \quad (A.6)$$

$$v_t^{\mathrm{cost,emission}} = \sum_u p_u^{\mathrm{fuel,nom}} \cdot v_{u,t}^{\mathrm{load}} \cdot p^{\mathrm{price,CO2}} \cdot p^{\mathrm{share,fossil}} \quad (A.7)$$

$$v_t^{\mathrm{cost,import}} = v_t^{\mathrm{el,import}} \cdot p_t^{\mathrm{price,el}} \quad (A.8)$$

In addition to the variable terms, fixed costs are calculated to determine the system's annual net profit. Eq. (A.9) presents the calculation of the fixed operating costs for the power generation and circular economy based on the unit nominal capacity. The annualized investment cost for the unit and process investments is calculated in Eq. (A.11) using the weighted average cost of capital, investment lifetime, and the investment present value (Eq. (A.10)).

$$p^{\mathrm{cost,OM,fix}} = p_u^{\mathrm{nom}} \cdot p_u^{\mathrm{cost,OM,fix}} \quad (A.9)$$

$$p^{\mathrm{cost,investment}} = p_u^{\mathrm{nom}} \cdot p_u^{\mathrm{cost,inv,spec}} \quad (A.10)$$

$$p_{u,t}^{\mathrm{payment}} = p^{\mathrm{cost,investment}} \cdot p_u^{\mathrm{WACC}} \cdot \left(1 + p_u^{\mathrm{WACC}}\right)^{p_u^{\mathrm{lifetime}}} / \left[\left(1 + p_u^{\mathrm{WACC}}\right)^{p_u^{\mathrm{lifetime}}} - 1\right] \quad (A.11)$$

For all dispatchable units generating heat, the fuel input is converted into heat output based on the load percentage and conversion efficiency, as shown by Eq. (A.12)

$$v_{u,t}^{\mathrm{th}} = p_u^{\mathrm{fuel,nom}} \cdot v_{u,t}^{\mathrm{load}} \cdot p_u^{\mathrm{eff,th}} \quad (A.12)$$

Variable renewable energy

Depending on the scenario options, the hourly wind generation is constrained equal to the sum of different option variables representing the utilization options (Eq. (A.13)). In all scenarios, local consumption and export options are available, whereas heat and circular options are added in the power-to-heat and power-to-circular economy scenarios, respectively.

$$p_t^{\mathrm{wind}} = v_t^{\mathrm{wind,local}} + v_t^{\mathrm{wind,export}} + v_t^{\mathrm{wind,heat}} + v_t^{\mathrm{wind,circular}} \quad (A.13)$$

System balances

Energy balance equations constrain the hourly operation of the power system (Eq. (A.14)) and district heating system (Eq. (A.15)). In the power system, the hourly demand is constrained equal to the sum of power transmission (imported power and exported wind), wind power used locally, solar power used locally, and the additional demand caused by the different scenarios. Similarly, the heat demand is constrained equal to the sum of unit production, and the production or demand of the different scenarios. The possibility to overproduce the demand or curtail the variable renewable power generation is not included. For the power transmission (Eqs. (A.16) and (A.17)), the hourly transmission is constrained below the maximum transmission capacity.

$$p_t^{\mathrm{el}} = v_t^{\mathrm{el,import}} - v_t^{\mathrm{wind,export}} + v_t^{\mathrm{wind,local}} + p_t^{\mathrm{solar}} - v_t^{\mathrm{el,circular}} - v_t^{\mathrm{el,vehicles}} \quad (A.14)$$

$$p_t^{\mathrm{th}} = \sum_{u \in U} v_{u,t}^{\mathrm{th}} + v_t^{\mathrm{th,heat}} + v_t^{\mathrm{th,circular}} \quad (A.15)$$

$$v_t^{\mathrm{el,import}} \le p_t^{\mathrm{trans,max}} \quad (A.16)$$

$$v_t^{\mathrm{wind,export}} \le p_t^{\mathrm{trans,max}} \quad (A.17)$$

Power-to-electric vehicles

In the power-to-electric vehicles ("P2EV") scenario, electric vehicles are considered as an additional power demand node that is included in the power system balance. The daily total charging requirement is determined by Eq. (A.18) using the number of electric vehicles, the average daily road transportation demand, and the specific power consumption, whereas Eq. (A.19) defines the total hourly maximum charging rate. The parameters are used with two constraints: Eq. (A.20) is applied in daily windows to ensure that the total daily charging requirement is met, and Eq. (A.21) is used to limit the hourly charging rate.

$$p^{\text{vehicles,demand}} = p^{\text{n,vehicles}} \cdot p^{\text{vehicles,distance}} \cdot p^{\text{vehicles,demand}} \tag{A.18}$$

$$p^{\text{vehicles,peak}} = p^{\text{n,vehicles}} \cdot p^{\text{vehicles,charge,max}} \tag{A.19}$$

$$\sum_t v_t^{\text{el,vehicles}} = p^{\text{el,vehicles,demand}} \tag{A.20}$$

$$v_t^{\text{el,vehicles}} \leq p^{\text{vehicles,peak}} \tag{A.21}$$

Power-to-heat

The power-to-heat ("P2H") scenario adds electric boiler capacity to the energy system. The capacity is considered as a heat generation unit, and its production (Eq. (A.22)) is therefore included in the district heating system balance equation. Consequently, income is gained from the sold district heat.

$$v_t^{\text{th,heat}} = v_t^{\text{wind,heat}} \cdot p_u^{\text{eff,boiler,electric}} \tag{A.22}$$

Power-to-circular economy

The power-to-circular economy ("P2CE") scenario adds multiple new elements to the energy system, affecting the power system and district heating system balance equations with new demand and production terms (Eqs. (A.23) and (A.24)). The electricity consumed by the circular processes is constrained equal to the wind power allocated for the circular processes (Eq. (A.25)).

$$v_t^{\text{el,circular}} = v_t^{\text{el,electrolysis}} + v_t^{\text{el,biodiesel}} \tag{A.23}$$

$$v_t^{\text{th,circular}} = v_t^{\text{th,electrolysis}} - v_t^{\text{th,biodiesel}} \tag{A.24}$$

$$v_t^{\text{wind,circular}} = v_t^{\text{el,circular}} \tag{A.25}$$

The hydrogen production of the electrolyzer is calculated using Eq. (A.26). Part of the electricity used is turned into process heat (Eq. (A.27)), which is integrated into the district heating system energy balance.

$$v_t^{\text{H2,electrolysis}} = v_t^{\text{el,electrolysis}} \cdot p^{\text{eff,electrolysis}} \tag{A.26}$$

$$v_t^{\text{th,electrolysis}} = v_t^{\text{el,electrolysis}} - v_t^{\text{H2,electrolysis}} \tag{A.27}$$

The produced hydrogen is stored in short-term storage, for which the hourly capacity is constrained between the minimum and maximum capacity (Eq. (A.28)). The hydrogen discharged from the storage can be presented as the change in capacity in consecutive hours (Eq. (A.29)). The hydrogen storage is initialized with half of the maximum capacity (Eq. (A.30)) and is expected to return to the initial state at the end of the time horizon (Eq. (A.31)).

$$0 \leq v_t^{\text{H2,storage,cap}} \leq p^{\text{H2,storage,cap,max}} \tag{A.28}$$

$$v_t^{\text{H2,storage,discharge}} = v_{t+1}^{\text{H2,storage,cap}} - v_t^{\text{H2,storage,cap}} \tag{A.29}$$

$$v_1^{\text{H2,storage,cap}} = 0.5 \cdot p^{\text{H2,storage,cap,max}} \tag{A.30}$$

$$v_1^{\text{H2,storage,cap}} = v_T^{\text{H2,storage,cap}} \tag{A.31}$$

The hydrogen storage is connected to the upgrading of the biogas. In Eqs. (A.32) and (A.33), the hourly raw biogas yield is used to determine the hourly volumes of methane and carbon dioxide, respectively. This purified methane can be directly sold whereas the carbon dioxide fraction is upgraded to biomethane using hydrogen. The Sabatier reaction (Eq. (A.34)), along with molar volumes and molar masses of carbon dioxide and hydrogen are used to determine the amount of hydrogen required for the upgrade as well as the resulting amount of synthetic natural gas. After upgrading, the total amount of biomethane therefore consists of two components; purified methane and upgraded synthetic natural gas (Eq. (A.35)).

$$p_t^{\text{CH4,purified}} = p_t^{\text{biogas}} \cdot p^{\text{fraction,CH4}} \tag{A.32}$$

$$p_t^{\text{CO2,purified}} = p_t^{\text{biogas}} \cdot (1 - p^{\text{fraction,CH4}}) \tag{A.33}$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{A.34}$$

$$p_t^{\text{CH4,total}} = p_t^{\text{CH4,purified}} + p_t^{\text{CH4,upgraded}} \tag{A.35}$$

The upgrading of the biogas is controlled with a binary variable (Eq. (A.36)). A constraint is applied to ensure that the hydrogen required for the upgrading, solved from the Sabatier reaction, is equal to the amount extracted from the hydrogen storage (Eq. (A.37)).

$$v_t^{\text{H2,upgrading}} = p_t^{\text{H2,required}} \cdot v_t^{\text{biogas,upgraded}} \tag{A.36}$$

$$v_t^{\text{H2,upgrading}} = v_t^{\text{H2,storage,discharge}} \tag{A.37}$$

Eq. (A.38) shows the income function for biogas production, in which a binary variable is also used to control the income from upgraded biogas. In scenarios other than power-to-circular economy, the option for the upgrading of biogas is excluded and the income function is simplified to Eq. (A.39), in which the amount and price of raw biogas is applied.

$$v_t^{\text{in,biogas}} = \left(1 - v_t^{\text{biogas,upgraded}}\right)\cdot p_t^{\text{CH4,purified}}\cdot \mathrm{p}^{\text{price,biogas}} + v_t^{\text{biogas,upgraded}}\cdot\left(p_t^{\text{CH4,purified}} + p_t^{\text{CH4,upgraded}}\right)\cdot p^{\text{price,biogas,upgraded}} \tag{A.38}$$

$$v_t^{\text{in,biogas}} = p_t^{\text{biogas}}\cdot p^{\text{price,biogas}} \tag{A.39}$$

For biodiesel production, the fish waste is divided into two fractions based on the hourly fish waste amount using a binary variable.

$$v_t^{\text{waste,feed}} = p_t^{\text{waste,amount}}\cdot\left(1 - v_t^{\text{waste,upgraded}}\right) \tag{A.40}$$

$$v_t^{\text{waste,biodiesel}} = p_t^{\text{waste,amount}}\cdot v_t^{\text{waste,upgraded}} \tag{A.41}$$

For the waste fraction used as fur animal feed (Eq. (A.40)), the income can be directly calculated (Eq. (A.42)).

$$v_t^{\text{in,waste,feed}} = v_t^{\text{waste,feed}}\cdot p^{\text{price,waste,feed}} \tag{A.42}$$

For the waste fraction to be upgraded into biodiesel (Eq. (A.41)), the amounts of processed waste oil (Eq. (A.43)), biodiesel (Eq. (A.44)) and glycerin (Eq. (A.45)) fractions are calculated based on defined yield percentages.

$$v_t^{\text{oil,amount}} = v_t^{\text{waste,biodiesel}}\cdot p^{\text{fraction,oil}} \tag{A.43}$$

$$v_t^{\text{biodiesel,amount}} = v_t^{\text{oil,amount}}\cdot p^{\text{fraction,biodiesel}} \tag{A.44}$$

$$v_t^{\text{glyserin,amount}} = v_t^{\text{biodiesel,amount}}\cdot p_t^{\text{fraction,glyserin}} \tag{A.45}$$

For the upgrading steps, the associated income and cost functions are defined in Eqs. (A.46) and (A.47). The income function (Eq. (A.48)) consists of income from sold biodiesel and glycerin, whereas the cost function (Eq. (A.49)) sums the costs from the required formic acid and methanol.

$$v_t^{\text{in,biodiesel}} = v_t^{\text{biodiesel,amount}}\cdot p^{\text{price,biodiesel}} + v_t^{\text{glyserin,amount}}\cdot p^{\text{price,glyserin}} + v_t^{\text{in,waste,feed}} \tag{A.46}$$

$$v_t^{\text{cost,biodiesel}} = v_t^{\text{oil,amount}}\cdot p_t^{\text{req,acid}}\cdot p^{\text{price,acid}} + v_t^{\text{biodiesel,amount}}\cdot p_t^{\text{req,methanol}}\cdot p^{\text{price,methanol}} \tag{A.47}$$

Finally, the power and heat demand of the upgrading steps are calculated based on the specific energy consumption in Eqs. (A.48) and (A.49).

$$v_t^{\text{el,biodiesel}} = v_t^{\text{oil,amount}}\cdot p^{\text{el,req,oil}} + v_t^{\text{biodiesel,amount}}\cdot p^{\text{el,req,biodiesel}} \tag{A.48}$$

$$v_t^{\text{th,biodiesel}} = v_t^{\text{oil,amount}}\cdot p^{\text{th,req,oil}} + v_t^{\text{biodiesel,amount}}\cdot p^{\text{th,req,biodiesel}} \tag{A.49}$$

References

[1] United Nations. Paris Agreement; 2015. [Online]. Available: https://unfccc.int/sites/default/files/english_paris_agreement.pdf. [accessed: 13-Aug-2019].

[2] Frankfurt School-UNEP Centre/BNEF. Global trends in renewable energy investment 2018; 2018. [Online]. Available: https://www.fs-unep-centre.org/ [accessed: 13-Aug-2019].

[3] IRENA. Renewable power generation costs in 2018. Abu Dhabi: International Renewable Energy Agency; 2019.

[4] IEA. Renewable capacity growth worldwide stalled in 2018 after two decades of strong e; 2019. [Online]. Available: https://www.iea.org/news/renewable-capacity-growth-worldwide-stalled-in-2018-after-two-decades-of-strong-expansion [accessed: 13-Aug-2019].

[5] IEA. Global Energy & CO2 Status Report; 2019. [Online]. https://www.iea.org/reports/global-energy-co2-status-report-2019 [accessed: 13-Aug-2019].

[6] IRENA. Global Energy Transformation: A roadmap to 2050. Abu Dhabi: International Renewable Energy Agency; 2018.

[7] Lantto R, Järnefelt V, Tähtinen M, Jääskeläinen A-S, Laine-Ylijoki J, Oasmaa A, et al. Commentary going beyond a circular economy: a vision of a sustainable economy in which material, value and information are integrated and circulate together. Industrial Biotechnology 2019;15(1):12–9. https://doi.org/10.1089/ind.2019.29156.rla.

[8] IRENA. Power system flexibility for the energy transition, Part 1: Overview for policy makers. Abu Dhabi: International Renewable Energy Agency; 2018.

[9] Cochran J, Miller M, Zinaman O, Milligan M, Arent D, Palmintier B, et al. Flexibility in 21st century power systems. NREL 2014.

[10] Paiho S, Saastamoinen H, Hakkarainen E, Similä L, Pasonen R, Ikäheimo J, et al. Increasing flexibility of Finnish energy systems—A review of potential technologies and means. Sustainable Cities and Society Nov. 2018;43:509–23. https://doi.org/10.1016/j.scs.2018.09.015.

[11] Lund PD, Lindgren J, Mikkola J, Salpakari J. Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renewable and Sustainable Energy Reviews May. 2015;45:785–807. https://doi.org/10.1016/j.rser.2015.01.057.

[12] Lantto (Ed) R, Järnefelt (Ed) V, Tähtinen M. Going beyond a circular economy. VTT Technical Research Centre of Finland. VTT Visions 2018. https://www.vtt.fi/inf/pdf/visions/2018/Going_beyond_a_circular_economy.pdf.

[13] Meschede H, Holzapfel P, Kadelbach F, Hesselbach J. Classification of global island regarding the opportunity of using RES. Applied Energy 2016;175:251–8. https://doi.org/10.1016/j.apenergy.2016.05.018.

[14] Child M, Nordling A, Breyer C. Scenarios for a sustainable energy system in the Åland Islands in 2030. Energy Conversion and Management 2017;137:49–60. https://doi.org/10.1016/j.enconman.2017.01.039.

[15] Cross S, Padfield D, Ant-Wuorinen R, King P, Syri S. Benchmarking island power systems: Results, challenges, and solutions for long term sustainability. Renewable and Sustainable Energy Reviews 2017;80:1269–91. https://doi.org/10.1016/j.rser.2017.05.126.

[16] Meschede H, Child M, Breyer C. Assessment of sustainable energy system configuration for a small Canary island in 2030. Energy Conversion and Management 2018;165:363–72. https://doi.org/10.1016/j.enconman.2018.03.061.

[17] Gils HC, Simon S. Carbon neutral archipelago – 100% renewable energy supply for the Canary Islands. Applied Energy 2017;188:342–55. https://doi.org/10.1016/j.apenergy.2016.12.023.

[18] Al Katsaprakakis D, Thomsen B, Dakanali I, Tzirakis K. Faroe Islands: Towards 100% R.E.S. penetration. Renewable Energy 2019;135:473–84. https://doi.org/10.1016/j.renene.2018.12.042.

[19] Garcia Latorre FJ, Quintana JJ, de la Nuez I. Technical and economic evaluation of the integration of a wind-hydro system in El Hierro island. Renewable Energy 2019;134:186–93. https://doi.org/10.1016/j.renene.2018.11.047.

[20] Notton G, Nivet ML, Zafirakis D, Motte F, Voyant C, Fouilloy A. Tilos, the first autonomous renewable green island in Mediterranean: A Horizon 2020 project. In: 15th International Conference on Electrical Machines. Sofia, Bulgaria: Drives and Power Systems (ELMA 2017); 2017. p. 102–5. https://doi.org/10.1109/ELMA.2017.7955410.

[21] Parkkari J. Ahvenanmaasta Suomen seuraava vientimenestys? Maakunta siirtyy uusiutuvaan energiaan, ja malli halutaan myydä Kiinaan ja Intiaan [Is Åland the Finland's next export success story? The region is transitioning to renewable energy and wants to sell the model to China and India]; YLE, 2018. [Online]. Available: https://yle.fi/uutiset/3-10127907 [accessed: 22-Oct-2018].

[22] Thomasson T, Kiviranta K, Hirvonen J, Tähtinen M. Assessing scenarios for fully renewable Åland Islands. Manuscript Submitted for publication 2020.

[23] Allwinds Ab. De åländska vindkraftverken [The wind power plants of Åland]; 2018. [Online]. Available: https://www.allwinds.ax/de-alandska-vindkraftverken/ [accessed: 05-Feb-2018].

[24] Allwinds Ab. The Wind Power of Åland Islands; 2018. [Online]. Available: https://www.allwinds.ax/wp-content/uploads/2018/01/Allwinds_Smart-Energy-Island.pdf. [accessed: 05-Feb-2018].

[25] Child M, Nordling A, Breyer C. The impacts of high V2G participation in a 100 % renewable Åland energy system. Energies 2018;11. https://doi.org/10.3390/en11092206.

[26] Pääkkönen A, Joronen T. Revisiting the feasibility of biomass-fueled CHP in future energy systems – Case study of the Åland Islands. Energy Conversion and Management May 2019;188:66–75. https://doi.org/10.1016/j.enconman.2019.03.057.

[27] Hart WE, et al. Pyomo: modelling and solving mathematical programs in Python. Mathematical Programming Computation 2011;3(219). https://doi.org/10.1007/s12532-011-0026-8.

[28] IBM. IBM CPLEX Optimizer; 2020. [Online]. Available: https://www.ibm.com/analytics/cplex-optimizer.

[29] Kraftnät Åland Ab. Kraftnät Åland Årsberättelse 2007–2018 [Annual report of Kraftnät Åland 2007-2018]; 2019. [Online]. Available: http://www.kraftnat.aland.fi/text.con?iPage=11&m=21 [accessed: 27-Jun-2019].

[30] Finnish Energy. District heating statistics; 2018. [Online]. Available: https://energia.fi/en/news_and_publications/publications/district_heating_statistics.html#material-view [accessed: 15-Oct-2018].

[31] Mariehamns Energi Ab. Årsberättelse 2017 [Annual report 2017]; 2018. [Online]. Available: https://issuu.com/straxkommunikation/docs/arsberattelse_2017. [accessed: 05-Feb-2018].

[32] Statistics and Research Åland (ÅSUB). Supply of some of the common oil products by the oil companies in Åland 1982-2018 by year and product; 2019. [Online]. Available: https://pxweb.asub.ax/PXWeb/pxweb/en/Statistik/Statistik_MI/?rxid=4f7d9b63-2d7c-4db9-aa9c-603a83bd8d03 [accessed: 20-Nov-2019].

[33] Finnish Meteorological Institute. Havaintojen lataus [Download the observations]; 2018. [Online]. Available: https://ilmatieteenlaitos.fi/havaintojen-lataus#!/ [accessed: 08-Nov-2018].

[34] Enercon GmbH. E-44; 2018. [Online]. Available: https://www.enercon.de/en/products/ep-1/e-44/ [accessed: 08-Nov-2018].

[35] Enercon GmbH. E-70; 2018. [Online]. Available: https://www.enercon.de/en/products/ep-2/e-70/ [accessed: 08-Nov-2018].

[36] Enercon GmbH. E-101; 2018. [Online]. Available: https://www.enercon.de/en/products/ep-3/e-101/ [accessed: 08-Nov-2018].

[37] Government of Åland. Energi- och klimatstrategi för Åland till år 2030 [Energy and Climate Strategy of Åland for 2030]; 2017. [Online]. Available: https://www.regeringen.ax/sites/www.regeringen.ax/files/attachments/page/lr[KK1]_energi_klimatstrat_2030.pdf [accessed: 08-Nov-2018].

[38] Nordpool. Historical Market Data; 2018. [Online]. Available: https://www.nordpoolgroup.com/historical-market-data/ [accessed: 15-Aug-2019].

[39] CLIC Innovation. Final joint report of the projects FLEXe DEMO and CEMBioFlex; 2019. [Online]. Available: https://flexens.com/wp-content/uploads/2019/03/Final_Report_FLEXe_demo_and_CEMBioFlex.pdf [accessed: 15-Aug-2019].

[40] Pöyry. Kraftnät Åland, Finland; 2016. [Online]. Available: https://www.poyry.com/sites/default/files/media/related_material/kraftnat_aland_case_story_a4_new.pdf [accessed: 05-Feb-2018].

[41] Ålands Skogsindustrier Ab. Verksamhetsberättelse 2017 [Annual report 2017]; 2018. [Online]. Available: http://www.skogsindustrier.ax/sites/www.skogsindustrier.ax/files/attachments/verksamhetsberattelse_2017.pdf [accessed: 13-Dec-2018].

[42] Ålandsmejeritet. Energisamarbete [Energy cooperation]; 2018. [Online]. Available: https://www.aca.ax/sites/www.aca.ax/files/upload/gastronomen_webb.pdf [accessed: 13-Dec-2018].

[43] Avsättning av slutprodukterna från en åländsk biogasanläggning [Disposal of the end products from a biogas plant in Åland] Renhållningsmyndigheten Ålands Miljöservice KF, 2018.

[44] Mariehamns Stad. Lotsbroverket; 2010. [Online]. Available: https://www.mariehamn.ax/globalassets/dokument/06_boende_miljo/boende/lotsbroverket_infobroschyr.pdf [accessed: 24-Jun-2019].

[45] Fifax. Fifax Ab; 2019. [Online]. Available: https://fifax.ax/en/om-oss/ [accessed: 24-Jun-2019].

[46] VTT. Puhtaan veden ja ravinteiden talteenotto saariston, veneiden ja kalajalostamon jätevesistä etenee koevaiheeseen [Recovery of clean water and nutrients from the wastewater of the archipelago, boats and fish processing plant is progressing to piloting]; 2019. [Online]. Available: https://www.vtt.fi/medialle/uutiset/puhtaan-veden-ja-ravinteiden-talteenotto-saariston-veneiden-ja-kalajalostamon-jätevesistä-etenee-koevaiheeseen [accessed: 25-Jun-2019].

[47] B. Bergman. Mervärde ur fiskrens-Projektrapport [Added value from fish waste - project report]; 2017. [Online]. Available: https://www.ha.ax/uploads/2018/04/bergman_mervarde-ur-fiskrens_2017.pdf [accessed:24-Jun-2019].

[48] ÅSUB. Avfallsstatistik 2016 [Waste statistics 2016]; 2017. [Online]. Available: https://www.asub.ax/sites/www.asub.ax/files/statistics/avfall16.pdf [accessed: 24-Jun-2019].

[49] Statistics and Research Åland (ÅSUB). Generated waste in Åland by waste type, year and hazardous/non-hazardous; 2017. [Online]. Available: https://pxweb.asub.ax/PXWeb/pxweb/en/Statistik/Statistik_MI/MI003.px/table/tableViewLayout2/?rxid=5fa57277-5d80-4c56-942f-20825742f80c [accessed: 27-Jun-2019].

[50] B. Bergman. Fiskrens, en outnyttjad resurs [Fish waste, an untapped resource]; 2017. [Online]. Available: https://fiskodlarna.ax/wp-content/uploads/2020/02/Bilaga-7.-Fiskrens-en-outnyttjad-resurs.pdf [Accessed: 27 -Jun-2019].

[51] Ronde H, Ranne A, Pursiheimo E. Integrated renewable energy solutions for seafood processing stations. In: Proceedings of the International Conference on Energy and Sustainable Development: Issues and Strategies (ESD 2010): 2010 June 2-4, Chiang Mai, Thailand. doi:10.1109/ESD.2010.5598777; 2010.

[52] Flexens – Smart Energy Åland. Bioenergi och avfallsbaserad energiproduktion [Bioenergy and waste-based energy production]; 2020. [Online]. Available: https://smartenergy.ax/biogas/.

[53] Allerborg M, Bergström J, Englöf J, Holroyd J, Hultin C, Reuter O. Rötning av bioavfall på Åland [Digestion of biowaste in Åland]. KTH Stockholm; 2015.

[54] Stallhagen. Årsberättelse 2017 [Annual report 2017]; 2017. [Online]. Available: http://www.stallhagen.com/content/uploads/2018/05/arsberattelse17_webb.pdf [accessed: 27-Jun-2019].

[55] Niemi P. Enzymatic fractionation of brewer's spent grain and bioconversion of lignin-rich fractions in a colon model in vitro; 2016. [Dissertation].

[56] Kärki J, Kouri S, Hurskainen M, Tsupari E, Alakangas E, Bajamundi C. Integrated utilization pathways for biogenic CO2 in biomass driven industry sectors; 2017. [Online]. Available: https://projectsites.vtt.fi/sites/BioCO2/www.vtt.fi/sites/BioCO2/PublishingImages/tiedotteet/5BO.4.4_presentation.pdf [accessed: 27-Jun-2019].

[57] Jentsch M, Trost T, Sterner M. Optimal use of power-to-gas energy storage systems in an 85% renewable energy scenario. Energy Procedia 2014;46:254–61. https://doi.org/10.1016/j.egypro.2014.01.180.

[58] Lecker B, Illi L, Lemmer A, Oechsner H. Biological hydrogen methanation – A review. Bioresource Technology 2017;245(Part A):1220–8. https://doi.org/10.1016/j.biortech.2017.08.176.

[59] Tsupari E, Kärki J, Vakkilainen E. Economic feasibility of power-to-gas integrated with biomass fired CHP plant. Journal of Energy Storage 2016;5:62–9. https://doi.org/10.1016/j.est.2015.11.010.

[60] S. Kouri, M. Hurskainen, J. Kärki, E. Tsupari, E. Alakangas, and C. Bajamundi. Integrated utilisation pathways for biogenic carbon dioxide in biomass driven industry sectors. Proceedings of the 25th European Biomass Conference and Exhibition (EUBCE 2017): 2017 June 12-15, Stockholm, Sweden. 2017.

[61] ÅSUB. Statistisk årsbok för Åland 2018 [Statistical Yearbook of Åland 2018]. Mariehamn; 2018. [Online]. Available: https://www.asub.ax/sites/www.asub.ax/files/attachments/page/statistisk_arsbok_for_aland_2018_1.pdf [accessed: 27-Jun-2019].

[62] Ruska M, Kiviluoma J, Koreneff G. Sähköautojen laajan käyttöönoton skenaarioita ja vaikutuksia sähköjärjestelmään [Scenarios of large-scale deployment of electric vehicles and their power system impacts]. VTT Technical Research Centre of Finland; 2010. [Online]. Available: https://www.vttresearch.com/sites/default/files/pdf/workingpapers/2010/W155.pdf [accessed: 27-Jun-2019].

[63] Finnish Transport Infrastructure Agency. Henkilöliikennetutkimus 2016 [Passenger Transport Survey 2016]; 2018. [Online]. Available: https://julkaisut.vayla.fi/pdf8/lti_2018-01_henkiloliikennetutkimus_2016_web.pdf [accessed: 27-Jun-2019].

[64] Paakkinen M, Pihlatie M, Peltola V, Pylsy P. Sähköautojen kotilataaminen: GASELLI-väliraportti 1. VTT Tutkimusraportti, Nro VTT-R-02416-18 [Home charging of electric vehicles: First interim report of the GASELLI project]. VTT Technical Research Centre of Finland; 2018.

[65] Ikäheimo J, Kiviluoma J, Weiss R, Holttinen H. Power-to-ammonia in future North European 100 % renewable power and heat system. International Journal of Hydrogen Energy 2018;43(36):17295–308. https://doi.org/10.1016/j.ijhydene.2018.06.121.

[66] ENERFISH Consortium. Integrated renewable energy solutions for seafood processing stations; 2012. [Online]. Available: https://www.shetlandrenewables.com/assets/files/WP6%20Enerfish%20Report%20D13%20Final%20Report.pd [accessed: 27-Jun-2019].

[67] Danish Energy Agency and Energinet. Technology Data - Energy Plants for Electricity and District heating generation. Danish Energy Agency; 2020.

[68] Statistics Finland. Statistics: Energy prices; 2018. [Online]. Available: http://www.stat.fi/til/ehi/2018/02/ehi_2018_02_2018-09-12_tie_001_en.html [accessed: 23-Nov-2018].

[69] Finnish Energy. District heating in Finland 2017; 2018. [Online]. Available: https://energia.fi/files/2948/District_heating_in_Finland_2017.pdf [accessed: 23-Nov-2018].

[70] Statistics Finland. Sähkön ja lämmön tuotanto 2017 [Power and heat production 2017]; 2018. [Online]. Available: https://www.stat.fi/til/salatuo/2017/salatuo_2017_2018-11-01_tie_001_fi.html [accessed: 13-Apr-2019].

[71] EEX. European Emission Allowances (EUA); 2019. [Online]. Available: https://www.eex.com/en/market-data/environmental-markets/auction-market/european-emission-allowances-auction#!/2019/12/10 [accessed: 10-Dec-2019].